

Unlocking The Potential of Lidar: Principles, Applications, And Future Prospects

Yifan Zheng *

Sydney Smart Technology College, Northeastern University, Qinhuangdao, 110819, China

* Corresponding Author Email: AlexanderMisikaNilevsky@gmail.com

Abstract. Light Detecting and Ranging (LiDAR) has been experiencing a surge in popularity within the realm of high-tech innovations. This article elaborates on the operational principles, structural intricacies, and scanning methodologies of contemporary LiDAR devices. Additionally, this article provides a comprehensive overview of the diverse array of applications that LiDAR technology finds utility in, ranging from remote sensing and transportation to geography, atmospheric science, and astronomy. In the context of Time of Flight (ToF) LiDAR, the underlying operational concept revolves around measuring the temporal delay of the laser beam's journey from the device to the target. Conversely, Frequency Modulated Continuous Wave (FMCW) LiDAR operates by quantifying alterations in the wavelength of the reflected laser in comparison to the originally emitted laser, leveraging the Doppler effect. LiDAR products serve as invaluable tools for geologists, enabling them to generate 3D maps for researching various targets such as forestry, coastline morphology, and river bathymetry. Meanwhile, atmospheric scientists harness LiDAR products to delve into studies concerning atmospheric composition and meteorological phenomena. In the foreseeable future, it is anticipated that LiDAR products will witness widespread adoption across an array of applications, including autonomous vehicles and beyond.

Keywords: LiDAR; ToF; FMCW; Remote sensing; autonomous vehicles.

1. Introduction

This paper starts from a brief introduction of the structure and working principles then dig further into the various applications. Conclusion and prospects for LiDAR technology and its application is the last part. According to the Tesla, the company has product 1.37 million cars in 2022, increased by 40 percent. And 1.31 million cars are delivered, increased by 47 percent. Autonomous vehicles have Integrated more and more high technologies, especially accompanied by detecting and ranging devices. Light detection and ranging (LiDAR) have similar working principle as Radio detection and ranging (Radar) [1]. In general, a standard LiDAR device records the entire journey time of a laser pulse from its transmission point to a designated target and then back to the capturing camera [1]. This research report focuses on the categorization and utilization of LiDAR technology. In terms of its design, LiDAR can be categorized as mechanical LiDAR, hybrid solid-state LiDAR, and solid-state LiDAR [1].

LiDAR are widely applied among various fields such as remote sensing, transportation, geography, atmospheric science, and astronomy. The remote sensing application includes measuring forestry and mapping river bathymetry as well as coastline. The transportation application is mapping a stereoscopic and accurate view of ahead of autonomous vehicles. Compared with mature technology like radio detection and ranging or ultrasound detection and ranging, LiDAR is a new technology which has several unique characters. With technological advancement, increased integration, and mass production, the price of FMCW LiDAR will decrease and the accuracy, scanning speed, and anti-interference capability will be improved. As the reliability increases, the application of the LiDAR will be applied in more fields.

2. Technologies analysis

LiDAR (Light Detection and Ranging) is an instrument that employs lasers for object detection and distance measurement. The operational principle of LiDAR entails emitting a laser pulse, which

is then captured upon reflection by a target [2]. This initial step is referred to as detection, and the subsequent computation of the distance between the LiDAR device and the target is termed ranging. A standard LiDAR system comprises four key components: a transmitting module, a receiving module, a scanning module, and a control module.

Transmitting module is mainly a laser generator which gives out photons. Receiving module is mainly a photon detector composed by an array of thousands of photodiodes. Those diodes are mainly avalanche photodiodes, which can produce quantities of electrons when a few even a single photon hit one photodiode, and each photodiode has the ability of sensing the photons at a certain frequency. Scanning module turns the laser to various direction to scan the area. Control module collects the time pause data from each photon detectors and calculate the distance of each direction.

2.1. Mechanical scanning LiDAR

A single fixed camera can only detect an object and measure its distance in a straight line, which is called 1D LiDAR. When the camera is fixed on a platform which can rotate horizontally, it turns into 2D LiDAR. When the platform can route both horizontally and vertically, the device is now a 3D LiDAR. With a mechanical turntable, a 360-degree horizontal measurement angle can be achieved by rotating the transmitter module. Figure 1 below shows the structure of a typical 2D LiDAR. Using servo motors to drive mirror can beam the laser and turn the laser into object direction. As mirror routes, the scanning system can scan and collect the data on s straight line. And owing to the rotation of the beam system, which is the cylindrical part in the figure below, the device can 360-degree scan the surroundings through horizontally route the scanning line [3].

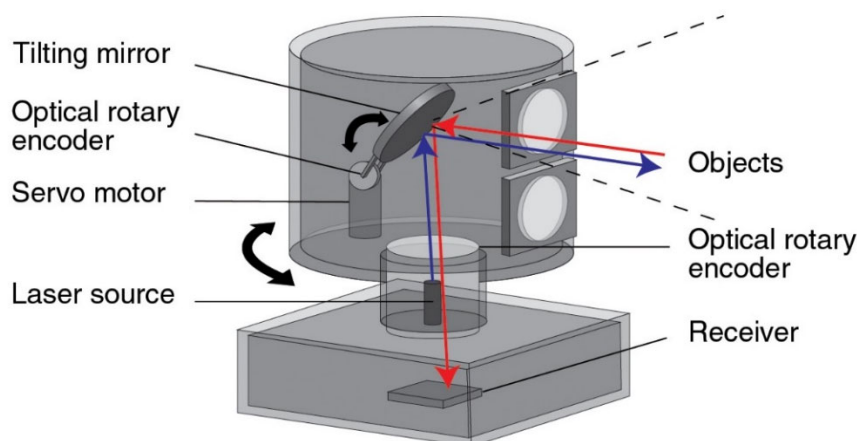


Fig. 1 Structure of Mechanical scanning LiDAR [3]

Mechanical lidar has fast scanning speed and strong anti-interference ability. However, mechanical lidar relies on the rotation of the mechanical structure to realize scanning, which has the disadvantages of severe physical wear, high cost, and bulky volume. In order to draw a finer point cloud map, mechanical lidar is often equipped with multiple transmitters and receivers, that is, 16 lines, 32 lines, 64 lines, etc. Multibeam lidar has better angular resolution and can capture smaller objects at a distance.

2.2. Hybrid Solid-State LiDAR

Common hybrid solid-state lidars include MEMS galvanometer, rotating mirror and prism. The Hybrid Solid-State LiDAR is shown in figure 2 [4].

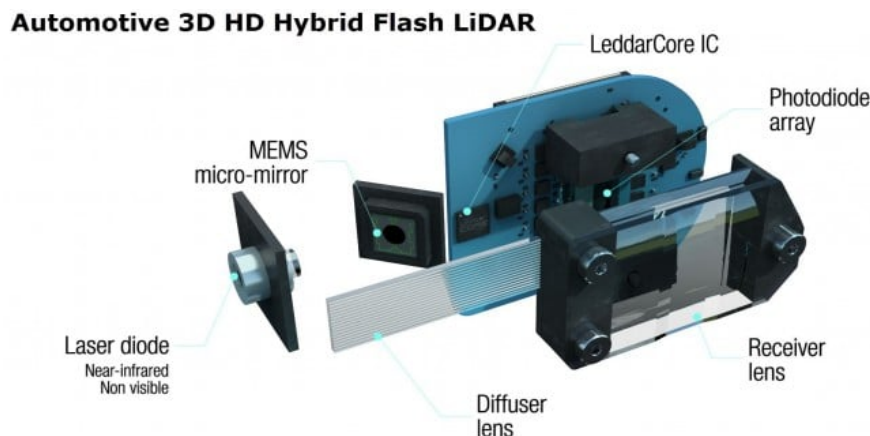


Fig. 2 Hybrid Solid-State LiDAR [4]

MEMS lidar uses a micro-mirror structure for laser beam deflection. The micro-vibration mirror is the core component of the MEMS lidar. It needs to have a flat optical mirror to reduce the rotating parts of the mechanical lidar and increase the integration. MEMS miniaturizes machinery, and the scanning unit becomes a MEMS micromirror. The driving methods of micropisms are more mature and extensive, such as electrostatic and electromagnetic.

The rotating mirror lidar keeps the transceiver module still and allows the motor to reflect the beam to a certain range of space during the movement of the rotating mirror, so as to realize scanning and detection. Its technological innovation is similar to that of the mechanical lidar [4].

Prism LiDAR, alternatively known as "Double Wedge Prism LiDAR," incorporates a pair of wedge prisms within its structure. As the laser beam traverses this LiDAR system, it undergoes a deflection upon passing through the first wedge prism and then undergoes another deflection upon encountering the second wedge prism. By precisely controlling the relative rotation speed of these two prisms, the scanning pattern of the laser beam can be effectively managed and manipulated.

2.3. Solid-State LiDAR

Solid-state lidar has no mechanical vibration structure, and all parts are fixed. Currently, there are two common technical paths: OPA and Flash.

OPA is an optical phased array, which consists of several units to form an array. Laser interference takes half a wavelength as a step, so the unit size of OPA is demanding, the process is extremely difficult, and the problem of signal processing and operation has not yet been well solved, and it is still in the laboratory stage. Working principle: The waves generated by vibration are superimposed on each other. According to the principle of interference, some directions reinforce each other, and some directions cancel each other [5]. The direction of enhancement is the laser scanning direction. Multiple light sources are used to form an array, and by controlling the time difference of each light source (the phase difference of light can synthesize a main beam with flexible angle and precise controllability), the object can be scanned three-dimensionally within a certain angle range.

Flash lidar adopts a camera-like working mode, and each pixel can record photon time-of-flight information. The emitted area laser is irradiated on the target. Since the object has three-dimensional space properties, the light reflected by different parts has different time-of-flight, which is detected by the focal plane detector array, and images are drawn according to the time-of-flight. Working principle: directly emit a large area of laser light covering the detection area in a short time, and then use a highly sensitive receiver to complete the drawing of the surrounding image, that is, flash.

2.4. TOF LiDAR

Pulsed Time-of-Flight (TOF) LiDAR operates by measuring the time delay between the emission of an optical pulse from the transmitter (TX), its reflection from the target, and its reception by the receiver (RX) [6]. The sensing distance can be calculated using the formula:

$$d = c \frac{\Delta t}{2} \tag{1}$$

Here, Δt represents the time delay, and c represents the speed of light. A depiction of the TX and RX signal in the time domain can be found in Figure 3.

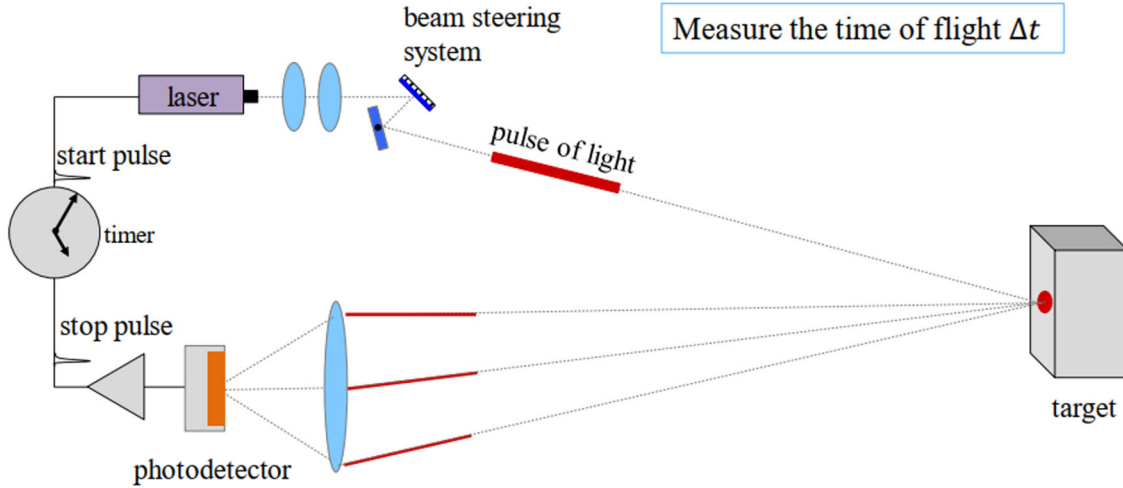


Fig. 3 TOF LiDAR [6]

The range resolution is constrained by the available timing resolution, primarily determined by electronic timing capabilities. Thanks to its high peak power, pulsed TOF LiDAR can effectively detect objects at greater distances while still adhering to eye-safety regulations due to its low average power output.

2.5. FMCW LiDAR

In contrast to Time-of-Flight (ToF) LiDAR, FMCW LiDAR employs a laser that emits a continuous optical signal modulated in frequency, while simultaneously receiving and analyzing the reflected signal. By examining the beat signal resulting from the interaction between the original and reflected signals, FMCW LiDAR can derive both distance and velocity information pertaining to moving objects [7]. This calculation process can be elucidated through the following pair of equations.

$$d = \frac{cT}{4B} \frac{f_u + f_d}{2} \tag{2}$$

$$v = \frac{c}{2f_c} \frac{f_u - f_d}{2} \tag{3}$$

In this context, where T denotes the modulation period, B signifies the chirp bandwidth, and c represents the speed of light, we define f_u as the beat frequency associated with the upward laser scan and f_d as the beat frequency for the downward laser scan. Both f_u and f_d encompass the Doppler frequency shift phenomenon. Additionally, f_c refers to the initial frequency, which is devoid of chirp, or commonly referred to as the optical carrier frequency, which is shown in figure 4 [1].

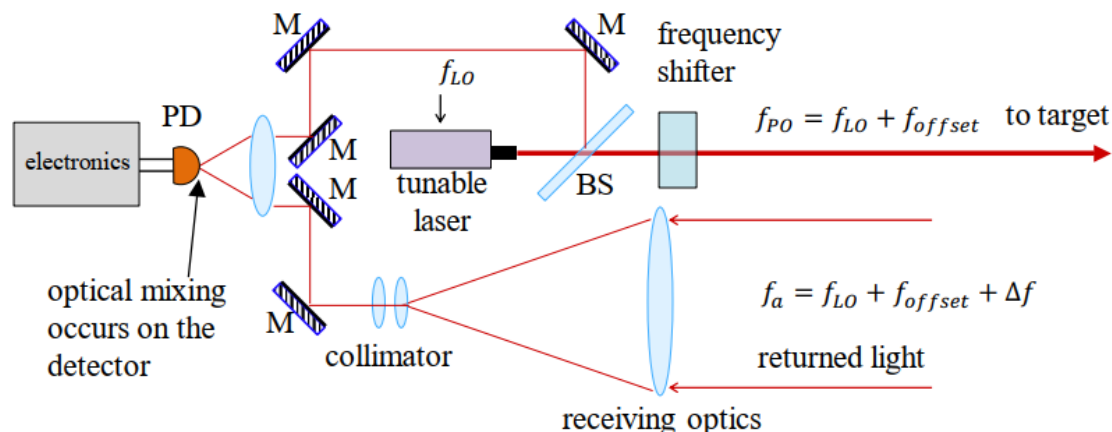


Fig. 4 FMCW LiDAR [1]

According to the Doppler effect, when the obstacle moves away from the detector, the wavelength of the reflected light becomes longer. On the contrary, when an obstacle approaches the detector, the wavelength of the reflected light becomes shorter. Due to the existence of phase difference, the reflected light and reserve part of the light emitted by the laser will have an interference superposition effect, amplifying the faint reflected light a hundred or even a thousand times, which makes it possible to measure the shift in wavelength and derive relative speed and distance from this.

3. Current applications

3.1. Remote sensing

LiDAR (Light Detection and Ranging) technology has emerged as a crucial tool in the field of remote sensing. Its applications are extensive, covering various domains including earth observation, Geographic Information Systems (GIS), and environmental research.

Firstly, LiDAR technology excels in terrain modeling and the creation of Digital Elevation Models (DEMs). By measuring the time, it takes for laser pulses to travel from the sensor to the Earth's surface, LiDAR can generate highly accurate digital elevation models. This capability is invaluable for creating topographic maps and simulating surface features, especially in urban planning, natural disaster monitoring, and hydrological research.

Secondly, LiDAR technology plays a significant role in vegetation analysis. Through LiDAR technology, scientists can create vegetation height models, aiding in the in-depth study of vegetation growth, coverage, and health [8]. This is of paramount importance in forestry, agriculture, ecological research, and urban greening projects.

Furthermore, LiDAR technology finds extensive application in urban planning and building monitoring. In urban planning, LiDAR can be used to develop detailed urban topographic maps, assess building heights, and analyze urban development trends. Additionally, it can be employed for monitoring buildings and infrastructure to detect any structural changes or damage, thereby contributing to sustainable urban development.

Lastly, LiDAR technology plays a crucial role in water resource management. It can be utilized to measure the surface elevations of water bodies such as rivers, lakes, and reservoirs, aiding in monitoring the distribution, flow, and water quality of water resources [9]. This is essential for effective water resource management and flood warning, helping society better respond to natural disasters and water resource challenges.

3.2. Transportation

The application of LiDAR technology in the transportation sector is rapidly increasing, providing excellent support for traffic management, intelligent transportation systems, and more.

Firstly, LiDAR plays a critical role in the field of autonomous vehicles. As one of the core perception technologies for self-driving cars, LiDAR sensors enable real-time environmental perception, including roads, vehicles, pedestrians, and obstacles, by installing LiDAR sensors on autonomous vehicles [10]. These instant data acquisitions are crucial for ensuring the safety of autonomous vehicles and effective decision-making.

Secondly, LiDAR sensors have strong potential in traffic flow monitoring. They can monitor real-time traffic information such as vehicle counts, speeds, and density on the roads, helping traffic management authorities better understand and optimize traffic flow, improving road efficiency. This is vital for alleviating traffic congestion and enhancing the efficiency of transportation systems.

Furthermore, LiDAR technology also plays an important role in road construction and maintenance. It can generate high-resolution terrain and road maps, aiding in the planning and maintenance of road infrastructure [11]. Additionally, LiDAR can detect road surface damage and wear and assess road safety, contributing to improved road quality and reliability.

Lastly, LiDAR data can be used for traffic signal optimization. Traffic signal systems can adjust signal timing in real-time based on LiDAR data to reduce traffic congestion and enhance traffic flow. This real-time adjustment helps reduce the occurrence of traffic accidents and improves the efficiency of the entire transportation system, making urban transportation safer and more convenient.

3.3. Atmospheric Science and Astronomy

LiDAR (Light Detection and Ranging) technology is gaining increasing attention in the fields of atmospheric science and astronomy, providing unique capabilities for the study of the Earth's atmosphere and outer space, leading to significant scientific achievements.

In the realm of atmospheric science applications, LiDAR technology serves several critical functions. Firstly, it can be employed to measure the concentrations and compositions of various gases in the atmosphere, such as ozone, water vapor, and particulate matter. This is crucial for a deeper understanding of atmospheric pollution, climate change, and the state of the ozone layer, aiding scientists in formulating policies and measures to address climate change and environmental pollution. Secondly, LiDAR, through the analysis of laser pulse scattering patterns, can provide data on atmospheric motion and wind fields. This is vital for researching phenomena like storms, cyclones, and atmospheric circulation [12]. Furthermore, LiDAR technology can also measure temperatures at different altitudes in the atmosphere, assisting in the study of temperature stratification and thermodynamic characteristics of the atmosphere, providing essential data for weather forecasting and climate research.

In the field of astronomy applications, LiDAR technology similarly plays a crucial role. It is used to measure the distances and motions of stars, planets, and other celestial bodies, providing astronomers with vital data to determine the positions, velocities, and orbits of celestial objects. This is essential for studying the structure and evolution of the universe, helping to uncover relationships between various celestial bodies in the cosmos [13]. Additionally, LiDAR technology is employed for instrument calibration, ensuring the precision and accuracy of astronomical observation instruments. This is crucial for conducting precise astronomical observations and researching various phenomena in the universe.

4. Conclusion

In contrast to conventional passive imaging methods like visible light and infrared radiation, LiDAR technology boasts distinctive advantages. Firstly, it revolutionizes the traditional 2D projection imaging paradigm by capturing in-depth surface data of the target. This enables the acquisition of comprehensive spatial information, facilitating the reconstruction of 3D target surfaces that faithfully represent their geometric intricacies. Additionally, LiDAR facilitates the extraction of abundant target surface reflection properties and movement velocities. This wealth of data greatly bolsters processes like target detection, recognition, and tracking, streamlining algorithmic

complexities. Furthermore, the incorporation of active laser technology endows LiDAR with characteristics such as exceptional measurement resolution, robust resistance to interference, heightened stealth detection capabilities, impressive penetration capabilities, and the ability to operate seamlessly in all weather conditions.

Though ToF LiDAR and MEMS scanning model is still the mainstream, solid-state FMCW LiDAR have already coming to prominence. Because FMCW method utilizing continuous laser, this new method can directly calculate the relative speed according to Doppler effect. And applying continuous light waves a better anti-interference ability under extreme weathers liking storms and fog. Besides, 1550 nm wavelength Infrared light is more friendly to humans' eyes than 850 nm visible light. With the improvement of the production process and the maturity of the technology, FMCW method will be widely used due to the improvement of cost performance in the near future.

References

- [1] Li N, Ho C P, Xue J, et al. A progress review on solid-state LiDAR and nanophotonics-based LiDAR sensors. *Laser & Photonics Reviews*, 2022, 16(11): 2100511.
- [2] Raj T, Hanim Hashim F, Baseri Huddin A, et al. A survey on LiDAR scanning mechanisms. *Electronics*, 2020, 9(5): 741.
- [3] Sandner T, Graßhoff T, Owe W D, et al. System integration of hybrid assembled large aperture Micro Scanner Array for fast scanning LiDAR sensors. *Journal of Optical Microsystems*, 2022, 2(1): 011004-011004.
- [4] Li C, Cao X, Wu K, et al. Blind zone-suppressed hybrid beam steering for solid-state Lidar. *Photonics Research*, 2021, 9(9): 1871-1880.
- [5] Van Nam D, Gon-Woo K. Solid-state LiDAR based-SLAM: A concise review and application. 2021 IEEE International Conference on Big Data and Smart Computing (BigComp). IEEE, 2021: 302-305.
- [6] Liu J, Sun Q, Fan Z, et al. TOF lidar development in autonomous vehicle. 2018 IEEE 3rd Optoelectronics Global Conference (OGC). IEEE, 2018: 185-190.
- [7] Martin A, Dodane D, Leviandier L, et al. Photonic integrated circuit based FMCW coherent LiDAR. *Journal of Lightwave Technology*, 2018, 36(19): 4640-4645.
- [8] Bhardwaj A, Sam L, Bhardwaj A, et al. LiDAR remote sensing of the cryosphere: Present applications and future prospects. *Remote Sensing of Environment*, 2016, 177: 125-143.
- [9] Van Leeuwen M, Nieuwenhuis M. Retrieval of forest structural parameters using LiDAR remote sensing. *European Journal of Forest Research*, 2010, 129: 749-770.
- [10] Gargoum S, El-Basyouny K. Automated extraction of road features using LiDAR data: A review of LiDAR applications in transportation. 2017 4th International Conference on Transportation Information and Safety (ICTIS). IEEE, 2017: 563-574.
- [11] Williams K, Olsen M J, Roe G V, et al. Synthesis of transportation applications of mobile LiDAR. *Remote Sensing*, 2013, 5(9): 4652-4692.
- [12] Sarkissian A, Keckhut P. Training of observational techniques for atmospheric sciences, planetology and astronomy provided by IPSL in France. *European Planetary Science Congress 2009*. 2009: 396.
- [13] Fredell M A, Carver G E, Chanda S, et al. Sub-nanometer band pass coatings for LIDAR and astronomy. *Lidar Remote Sensing for Environmental Monitoring XV*. SPIE, 2015, 9612: 112-117.